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Risk assessment of estuaries under climate change: Lessons from Western Europe

Jaak Monbaliu [a,*], Zhongyuan Chen [f], Didier Felts [b], Jianzhong Ge [f], Francois Hissel [b], Jens Kappenberg [c], Siddharth Narayan [d], Robert J. Nicholls [d], Nino Ohle [e], Dagmar Schuster [e], Janina Sothmann [c], Patrick Willems [a]

[a] KU Leuven Civil Engineering Department, Hydraulics Laboratory, Kasteelpark Arenberg 40, postbus 2448, 3001 Leuven, Belgium
[b] CETMEF (Institute for maritime and inland waterways), 134 Rue de Beauvais CS 60039, 60280 Margny-les-Compiègne, France
[c] Helmholtz-Zentrum Geesthacht (HZG), Max-Planck-Straße 1, 21502 Geesthacht, Germany
[d] Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Southampton SO17 1BJ, United Kingdom
[e] Hamburg Port Authority (HPA), Neuer Wandrahm 4, 20457 Hamburg, Germany
[f] State Key Laboratory of Estuarine and Coastal Research (SKLEC), East China Normal University,3663 N. Zhongshan Rd, 200062 Shanghai, PR China

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ABSTRACT

Climate change with rising sea levels and possible changes in surge levels and wave climate will have a large impact on how we protect our coastal areas and cities. Here the focus is on estuarine locations not only affected by tide and surge propagation, but also potentially influenced by freshwater discharge. Mitigation measures might be diverse ranging from pure hard 'engineering' solutions all the way to significant realignment. The variation in the type/origin and extent of the flood sources greatly influences subsequent risk management measures. At the same time, society is increasingly demanding that we take a holistic view on risk management, embracing and balancing safety, ecological and socio-economic aspects. This requires that all these diverse factors need to be considered together and integrated. In this context, the Source–Pathway–Receptor (SPR) approach offers a powerful holistic tool to investigate changing risk connected to extreme events.

The traditional SPR approach with a consecutive treatment of the flood, pathway and receptor is well understood and is widely used in coastal flood risk analysis. Here an enhanced 2D conceptual version of the SPR method is used to better describe the system and to allow flexibility in considering multiple scales, flood sources and pathways. The new approach is demonstrated by three estuarine case studies in western Europe: the Gironde estuary, France; the Dendermonde region in the Scheldt estuary, Belgium; and HafenCity (Hamburg) in the Elbe estuary, Germany. They differ considerably in the surface area considered, in the type of flood sources, and hence also in the SPR configuration. After a brief introduction of the typical characteristics of the three study sites including some lessons learned from past flood protection measures, the differences in application and results of the SPR approach are discussed. Emphasis is on the specific aspects for each study site, but embedded in a generic SPR framework. The resulting generic lessons learned about the flood sources and how this shapes subsequent analysis are transferable to numerous important estuaries worldwide.

1. Introduction

Estuaries and coastal areas are ecologically rich, often densely populated and of vital economic and social importance across Europe and the world. They are directly affected by sea-level rise, leading to higher extreme water levels. Also other aspects of climate change may have a significant additional impact on coastal flood risk (positive or negative). Possible changes in atmospheric circulation, related sea level pressure patterns and wind climate may result in changes of (extreme) wave conditions and storm surges. Typically estuaries combine threats from the terrestrial and the ocean side. The effects of changes in sea level interact with changes in rainfall and evapotranspiration patterns and consequent inland run-off in a non-linear way. The tide propagation characteristics may be altered and the location where a negative impact occurs is not necessarily at the location of the change. In addition, non-climate effects may be important such as localized subsidence of low-lying land (increasing potential flood depths and hence flood consequences) and capital dredging for navigation which will increase water depths and allow the tide and surges to propagate further upstream. Winterwerp (2013) gives 5 examples of 5 European ports (Antwerp on the Scheldt, Bremen on the Weser, Hamburg on the Elbe, Nantes on the Loire and Papenburg on the Ems) situated more than 50 km from the mouth of the estuary where the tidal range has increased in the last 100 years due to deepening and canalization. The increase of tidal range necessarily needs to have an effect on low and/or high water levels but to which extent high waters increase and low waters decrease depends on the shape of the estuary (Van Rijn, 2010,

* Corresponding author. Tel.: +32 16321661.
E-mail address: jaak.monbaliu@bwk.kuleuven.be (J. Monbaliu).

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2011). Wherever the site, all these factors need to be considered and the Source–Pathway–Receptor–(Consequences) SPR(C) methodology facilitates such an approach (Evans et al., 2004; Narayan et al., 2012, this volume). The C (Consequence) part of the SPRC methodology falls outside the scope of this paper and will – with the exception of the Gironde study site – not be discussed in detail.

The only certainty of what the future will bring us is uncertainty. Exploring this uncertainty is now widely accepted as good practice to study potential impacts of climate change, to investigate the effect of different mitigation options and to develop appropriate management plans. Global and regional climate model studies incorporate uncertainty in their model output through ensemble modeling, either through a perturbation of physics approach of an individual model or through ensembles of different models, illustrated by Lowe et al. (2009) and Grabemann and Weisse (2008), respectively. Weisse et al. (in press) give an assessment of the climate projections at the THESEUS study sites, including those considered in this paper.

This paper demonstrates the application benefits of the SPR(C) approach to investigate the possible impact of climate change on three specific areas that are situated in large European estuaries, with a focus on flood sources. For the Scheldt estuary the area of Dendermonde, Belgium, is chosen because of its particular sensitivity to the combined effect of rainfall-induced runoff (upstream discharge) and downstream surge levels including sea-level rise (Ntegeka et al., 2012). Surge levels, sea level rise and rainfall are all potentially affected by climate change. HafenCity in Hamburg on the Elbe, Germany, is an attractive residence and commercial area developed outside the dikes on an old port area and hence the impacts of increased water levels because of sea level rise and storm surges are directly and immediately felt. For the Gironde, France, the area downstream of Bordeaux is considered. The first two case studies consider rather small areas more upstream the estuary. In contrast, the Gironde case has a much larger extent both in space as in terms of variety of challenges. Contrary to the other sites, it also contains the lower part of the estuary where next to sea level rise and storm surge, also wave action is important.

Although the three sites are nearby in planetary terms, it proved impossible in practice to use the same tools and to come up with a homogeneous set of climate scenarios. The difference in traditions (existing flood protection plans and flood protection philosophy and strategy), in historical choices (choice of values for sea level rise by local stakeholders or decision for urban development outside the existing dike system as in HafenCity), in system characteristics (small versus large spatial scale, differences in dominant flood sources), in previous experience and knowledge (existing hydrodynamic model implementations, previous experience with climate scenario's for rainfall-run-off in the Dender basin) and in stakeholder needs at the different study sites (e.g. implementation of a Decision Support System for the Gironde during the THESEUS project, added value of combined rainfall-runoff and tide-surge climate scenarios study for the Dendermonde area), led to differences in the details of the climate scenarios used including differences in the assumption on sea level rise and difference in the tools (hydrodynamic and wave models) used. Details about this are given when describing the different sites. It can however be considered a strength of the SPR(C) approach is that it on the one hand could still be applied and on the other hand added insight in the risk assessment notwithstanding the various spatial scales and different amounts of detail in each of the study sites.

2. The SPR approach

The Source–Pathway–Receptor (SPR) approach is a well understood and widely used approach in coastal flood risk analysis. It was first adopted from pollution studies by the Foresight Future Flooding project in the UK and has been used in several flood risk assessments since Evans et al. (2004). The traditional use of the approach is a straightforward consecutive (1D) treatment of the coastal floodplain, consisting of a flood source leading through pathways to flood receptors. In this paper an enhanced 2D conceptual version of the SPR method is used to better describe the system and allow flexibility in considering multiple scales, flood sources and pathways (Narayan et al., 2012, this volume). The approach towards the application of this conceptual model was the same for all three estuaries: a large-scale SPR model applied to the estuary as a whole provides a way to identify main units within the estuary, and a more detailed small-scale SPR model for the specific unit of interest. In the Scheldt estuary the SPR results on the affected areas are compared with existing flood maps. In the Gironde, the SPR methodology is linked to a full-scale Decision Support System that maps and quantifies risk.

The 2D SPR model diagrams for each site are built for the natural floodplain of the maximum considered event. This can be done manually using e.g. Microsoft Publisher 2010, a standard program in Microsoft Office 2010, but can also be automated in a GIS environment. From these diagrams, system-level information is extracted about each floodplain and its flood sources. One such metric that is described here is the relative exposure of floodplain elements. The elements are classified in terms of exposure based on their distance away from the flood source expressed in number of links. Elements that are less than two links away from the flood source — i.e., elements that have one or zero intervening elements between themselves and a flood source, are classified as exposed. Elements further than two links away from sources are termed 'far elements'. The choice of two links is an arbitrary choice to differentiate element exposure, based on the reasoning that in most urban floodplains the first element encountered would function as a flood defense. The validity of this assumption should be verified for each study site. In this paper we have limited the discussion to two links. Three aspects of the floodplain are analyzed in each site: a) the relative percentages of different land-uses across the most exposed elements; b) the average number of flood sources per floodplain element and; c) the critical direction of flooding corresponding to maximum exposure of floodplain elements.

The direction of flooding is calculated based on flood source — floodplain element links as follows:

1. Using a coordinate system with the regular convention of N–S as the y-axis and the center of the floodplain as the origin, the flood sources are categorized as North (N), South (S), East (E) or West (W).
2. The number of floodplain elements exposed to each source is tallied. Only floodplain elements at most two links away from the source are taken into consideration. The numbers obtained are used to calculate the coordinates of a point: the x-coordinate being the difference between W vs E and the y-coordinate the difference between N vs S.
3. The critical direction of flooding is estimated as the angle of the arctangent line from the origin to the calculated point. Since the flood sources are discretized into North, South, East or West in the SPR, the dominant flood direction indicates the predominant source in terms of the number of linked, exposed floodplain elements. Note that this is a way to visualize the dominant flooding direction (flood source) but that the resulting direction is not connected to real world co-ordinates.

To illustrate the procedure, we refer to Fig. 6 for a simple example. In this example there are seven floodplain elements and two sources. Source S1 (North) is connected to four floodplain elements that are maximum two links away: floodplain elements 24, 25 and 26 are 1 link away and floodplain element 27 is two links away. Source S2 (East) is connected to seven floodplain elements: floodplain elements 26, 27, 28, 29 and 30 are 1 link away and floodplain elements 25 and 24 (linked via element 27) are two links away. The arctangent of 7 pointing west and 4 pointing south, gives a dominant flood direction of 240° from North.

Extreme coastal water level is a key parameter for assessing coastal flood risk and changes in the future climate. It is the superposition of a slowly changing mean sea level, astronomical tides and storm induced surge.[1] River flow and waves are, depending on the local situation, two other possible sources of flooding in an estuary. The influence of river flow rate will depend on the ratio between tidal flow and river flow. It will be important in those locations where fresh water exchange is considerable with respect to the tidal exchange flow. Waves influence flooding by set-up and overtopping/breaching mechanisms. They can become important in situations where there is a large fetch which is typical in the downstream parts of an estuary. All these are called source drivers in the SPR approach:

1. Mean sea level — the effect of mean water level change on extreme water level change. Note that where land movement is thought to be an important coastal process, it could be treated as a separate Source Driver and added to the effect of climate-induced oceanic changes. Sea level rise (SLR) due to climate change was found to be relevant in all three sites.
2. Wave height — the direct change in extreme wave height due to changing wind characteristics and the indirect change due to depth change produced by mean sea-level change described above.
3. Surges — the change in extreme sea level due to direct change in the surge component caused by changing storm characteristics (this is separate from the effect of mean sea-level change).
4. River flow — the change in extreme river volume/flow due to change in inland precipitation, if appropriate.

3. The Scheldt estuary

3.1. Current characteristics

The Scheldt estuary is part of the Scheldt basin (Fig. 1). The estuary is characterized by a multi-channel system in the downstream part with many sandbanks. More upstream it is a one channel system. The intertidal areas are of high nature value, with potentially high primary productivity. Migrating birds are therefore attracted to this excellent habitat. The Scheldt also serves as shipping route to the major harbor of Antwerp. The part of the estuary in The Netherlands is essential rural, whereas its part in Belgium is more densely populated and known for its intense industrial activities. From the mouth of the Scheldt near Vlissingen in the Netherlands, the tide propagates 160 km to Ghent in Belgium, where it is artificially stopped by a lock weir. Due to the geometric characteristic of the estuary the tidal amplitude increases all the way to Rupelmonde (by a factor around 1.4 some 15 km upstream of Antwerp at km 110 from the mouth). From there the amplification factor decreases to become approximately 1 near Dendermonde (at km 130) and then further decreases until Ghent (amplification factor of 0.55 at km 160 from the Vlissingen mouth) (Van Rijn, 2010, 2011).

3.2. History and functions

Land reclamation starting in the middle ages, capital and maintenance dredging on behalf of navigational needs and sea level rise have continuously increased tidal range and storm surge levels. For example the mean tidal range has increased by more than 1 m between 1900 and 2010 (from 4.4 to 5.3 m in Antwerp; Van Rijn, 2010, 2011). The largest portion (roughly 75%) of this increase in tidal range is seen as an increase in mean high water level, the remaining part (about 25%) is due to lowering of the mean low water level. The location of the highest mean water level has also moved upstream. VNSC (2010) has included water level as an indicator for assessing safety against flooding and gives detailed curves regarding the changes in high and low water levels along the estuary. More detailed physical interpretation using the theoretical principles of tide and tide propagation theory can be found in Pieters et al. (2005). Several important floods have hit the area. Still in recent memory are the disastrous flood of 1953 mainly in the Netherlands and the flood of 1976 which mainly hit Flanders. They led to the major coastal defense plans of the Delta Works in the Netherlands, completed by the installation of the storm surge barrier (Maeslandkering — used for the first time in 1997[2] on the Nieuwe Waterweg (Rotterdam area) and to the implementation of the Sigma Plan in Belgium. Execution of such plans takes decades, and these coastal defense plans have been revised along the way. The original intention of the Delta works was the closure of all mouths (except for the Western Scheldt). Largely due to ecological pressure, plans for the Eastern Scheldt were changed by building a gated storm surge barrier. Also the original Sigma Plan has been revised fairly recently based on a social cost benefit analysis, and new insights based on the creation of room for water (flood areas) have been integrated with the need for safety, nature and economic activity. Largely because of the economic activities in the harbor of Antwerp the fairway has been deepened and widened (most of it since 1970). In order to deal with the complex management of this estuarine system with on first view opposing interest of nature development, safety and economic development, there is an international Flemish–Dutch Scheldt Commission. A long term vision 2030 and an intensive monitoring strategy have been worked out to follow up on a set of indicators (LTV 2030; VNSC, 2013).

3.3. Fresh water input

The Scheldt basin is a relatively small catchment (nearly 22,000 km^2). Polder areas that drain directly into the sea are part of the basin but do as such not contribute to the discharge of the Scheldt. The Scheldt river itself has an average discharge of about 120 m^3/s. This is small in comparison with the tidal discharges at the mouth. Therefore fresh water flow does not influence water levels towards the downstream end. However more upstream the combination of high rainfall-runoff discharges and high tidal water levels may be important. This is particularly the case for the Dendermonde area (Fig. 1) where the combination of both leads to higher risk levels.

3.4. Climate change scenarios

Three future climate scenarios were selected for impact studies for the Dendermonde region in the 2080s: i) an extreme scenario (S1) combining an extreme SLR of 2 m with an increase in surge levels of 21% and an increase of 30% in upstream flow discharges; ii) a high scenario (S2) only differing from the extreme in the assumption on SLR (now set at 0.6 m); and a mean scenario (S3) where a SLR of 0.6 m is combined with a more moderate estimate of 6% for the surge levels and 16% for the upstream flow discharges. For the Dendermonde area in Scheldt estuary both rainfall-runoff and tide-surge propagation are important sources for flooding risk. These scenarios result from considerable experience with possible effects of climate change on rainfall-runoff for the Dendermonde area. They are based on detailed analysis and downscaling of PRUDENCE, ENSEMBLES and CERA databases containing several global and regional climate models and scenarios (see Ntegeka et al., 2012; Weisse et al., in press, for more details). Running all of these scenarios is impossible or at least very impractical for further detailed analysis. Therefore a reduced set has been used to do the detailed hydrodynamic model calculations and in depth analysis. In this case study the existing experience of possible future climate effects on rainfall-runoff, has been extended with original work on possible climate effects on surge and surge propagation in the Scheldt estuary. The extension takes into account the correlation between surge and rainfall in the different scenarios used.

[1] Astronomical tides are assumed unchanged.

[2] http://www.rijkswaterstaat.nl/water/feiten_en_cijfers/dijken_en_keringen/europoortkering/maeslantkering/.

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Fig. 1. The Scheldt basin district and the location of the Dendermonde area.
Adapted from International Scheldt commission.

3.5. Flood protection and hazards

The focus here is on the Dendermonde section of the Scheldt estuary only, a small area of some 30 km^2. However, the area is flood prone area at the confluence of the Scheldt river and its main tributary river, the river Dender. The Dender and Scheldt water levels are in that area influenced by the bi-directional interactions that exist between both rivers. There are many dense urban subareas and infrastructures in that region, which makes the region very vulnerable to flooding (Fig. 2). The Dender has very strong temporal river flow fluctuations. It is a river that responds very quickly to rainfall over the upstream catchments. In Dendermonde, the flow can be as low as 10 m^3/s in dry summer periods and can rise to more than 100 m^3/s in wet winter periods. To improve navigation, the tidal effects downstream the Dender were reduced by a lock weir, built at Dendermonde mid-19th century, and the river was canalized (starting from the 17th century) by several other lock weirs along the river. During high tide, the weir of Dendermonde is closed and together with two more weirs upstream, carefully regulated. During high tide periods, the upstream flow volumes are stored in the river stretches between the weirs. The river stretches act then as storage reservoirs. The stored volumes are released during low tide periods to the Scheldt, however still maintaining minimum water levels. During periods with extremely high tidal levels in the Scheldt and/or extremely high upstream Dender flows, floods can occur due to: i) Scheldt levels exceeding the Scheldt dike crests (or breaching), or ii) water storage along the Dender exceeding the river's storage capacity (Dender dike overtopping). The latter can be due to prolonged high tidal levels (hence long closure of the downstream Dender weirs), or high upstream Dender flows, or to both effects combined.

3.6. Hydrodynamic and flood model

In order to translate changes in downstream surge levels including SLR and changes in upstream discharge to changes in river water level and inundation related variables, a technical translation is needed in the form of a hydrodynamic or conceptual river model accompanied with an inundation model. For the river part, two types of models were considered: i) a full hydrodynamic model of the Scheldt and Dender rivers, implemented in the MIKE11 modeling platform of DHI Water & Environment; ii) a simplified conceptual river model for 7 points along the Scheldt and 3 points along the Dender, following the spatial discretization of the flood sources (hydraulic loading) in the SPR framework. For translating the river water levels simulated with those models to inundation related variables (inundation levels, spatial extent), the same two types of models were considered: (i) a quasi-2D floodplain model, implemented in the MIKE11/MIKE-GIS platform, where the flood plains along the river are represented by a network of flood branches and spills. The spill levels are determined by the topographical elevations in contrast to the flood branches which are topographical depressions (Willems et al., 2002; Willems, 2013); ii) a

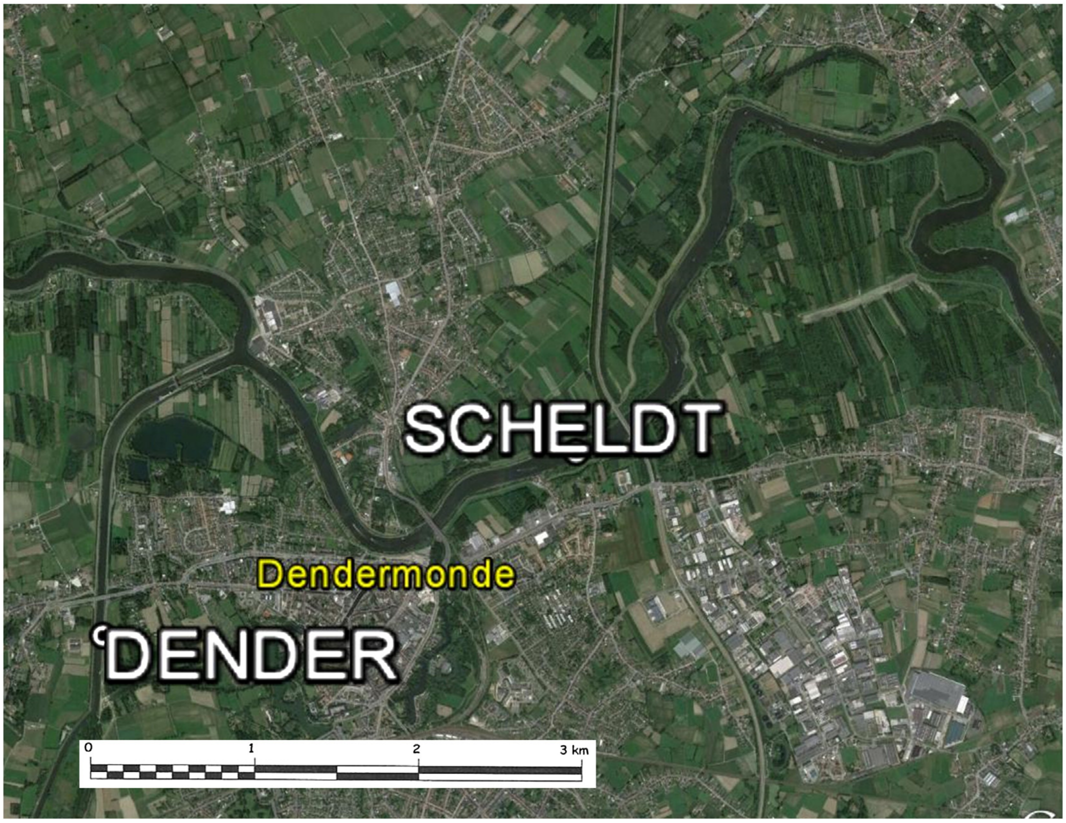

Fig. 2. Aerial view of the Dendermonde area located at the confluence of the rivers Scheldt and Dender.

simplified conceptual inundation model, considering the pathway elements in the SPR framework. In both cases, the simplified model was calibrated to the full hydrodynamic model. The full hydrodynamic model allows us to consider the most relevant physical processes, whereas the conceptual model has a reduced computational time and is better suited for integration in the SPR framework. The conceptual inundation model uses a linked-storage-cell approach where each element of the SPR is considered as a reservoir with an average elevation and a storage volume based on a storage depth variable which is used to calibrate the model. Flood water from the source(s) is spread across the floodplain through these elements until all the elements are full. The method is simple and provides rapid, basic information on flood extent and depth. The accuracy of the model is dependent on the resolution of the 2D SPR elements.

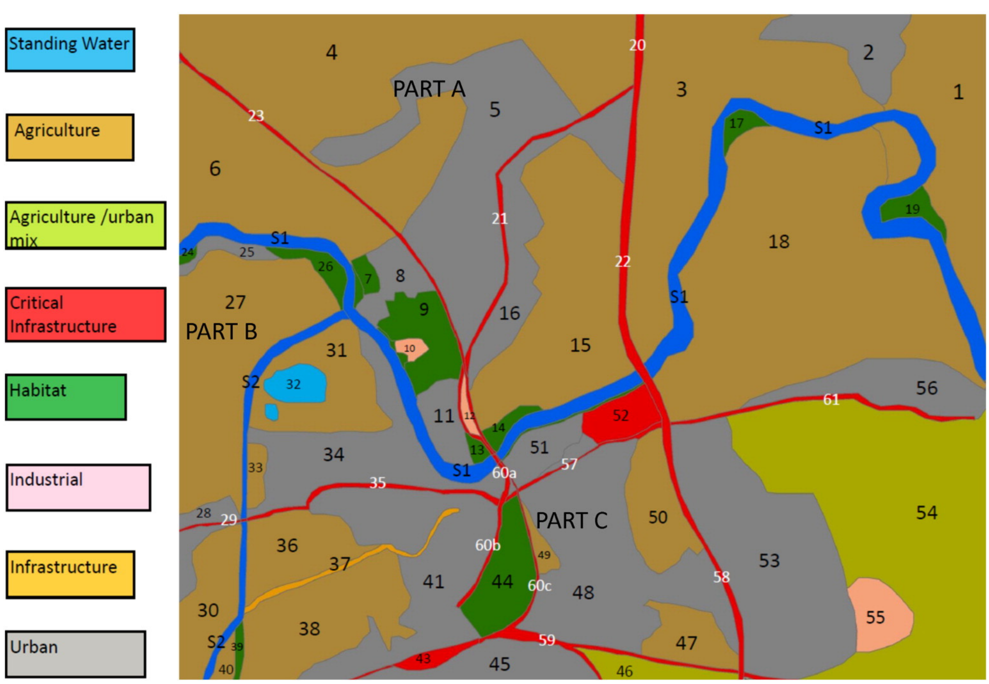

Fig. 3. Land use map of the Dendermonde area.

3.7. Schematic representation of the SPR model

The 2D SPR model for the Dendermonde area is built using two basic inputs: a map of the floodplain indicating the maximum flood extent and the constituent land-use polygons and a digital elevation model. The digital elevation model is used to record data on polygon elevations for use in the quantitative SPR analyses. The land-use map is typically to be created by the users. This gives these users flexibility in defining specific floodplain elements of non-local scale resolution that are known to be relevant to flood risk within the floodplain, such as defense elements, natural coastal elements or inland features such as roads or pumping stations. Fig. 3 shows the land-use map for the Dendermonde area.

The construction of the 2D SPR is flexible in terms of data requirements and element representation. The detail and type of elements represented reflect existing knowledge of the floodplain. While a degree of spatial representation is maintained to be able to map the elements onto a floodplain map, the key aspects that are preserved in the SPR system diagram are the topology and links. Elements can be modified and links added or removed when this knowledge is improved. For instance a link may be added between non-adjacent critical infrastructure elements, such as a power plant and a pumping station. The combination of the digital elevation model (DEM) with the 2D SPR serves as an effective way of ensuring that key floodplain elements are not missed due to resolution issues. Furthermore, since all mapped elements are represented in the model, assumptions about individual elements become explicit to users. Note that the system diagram presented here is manually constructed from a GIS-based land-use map. 2D SPR construction for this site has also been automated in ArcGIS for subsequent integration with flood mapping models. However a manually constructed map was found to be better for visualization and to facilitate a participatory mapping approach.

3.8. Findings

The 2D SPR in Fig. 4 represents part C of the Dendermonde area in Fig. 3. It highlights the two flood sources to the Dendermonde floodplain elements. It contains the area to the South of the Scheldt and to the East of the Dender in Fig. 3. Most elements are directly exposed to one source, though the maximum is two. The dominant flood direction is 66° below the W–E axis indicating the slight dominance of the northern source over the western source in terms of number of flood source — floodplain element links. Fig. 5 shows the relative percentage distributions of the different land-uses classes across the exposed elements.

As it is situated on relatively high ground, the frequency of flooding is rather limited for the city of Dendermonde. It is relatively safe from flooding. However, if floods occur, the consequences are severe. The 2D SPR makes assumptions explicit and structures understanding of the complex Scheldt-Dender system, the different flood sources and pathways (as described above) and the interactions. Since flooding in Dendermonde is driven predominantly by elevation rather than land-use, the 2D SPR by itself did not add knowledge regarding the flood risk. The construction of the 2D SPR did, however, provide knowledge regarding regional differences and severity of the consequences. For example, the region to the south-west of the Scheldt-Dender conjunction (part B in Fig. 3) was highlighted in the SPR and the flood model as being more flood-prone. Though the land-use map shows this floodplain to contain assets of relatively lower economic value (Fig. 3). The DEM identifies the floodplain as lying below river flood levels therefore making it more susceptible to flooding. The 2D SPR for this floodplain area is shown in Fig. 6.

This SPR conceptual model represents elements across a wide range of spatial resolution — as small as 15 m for the road and as large as 2000 m for the agricultural areas. The floodplain extent as well as

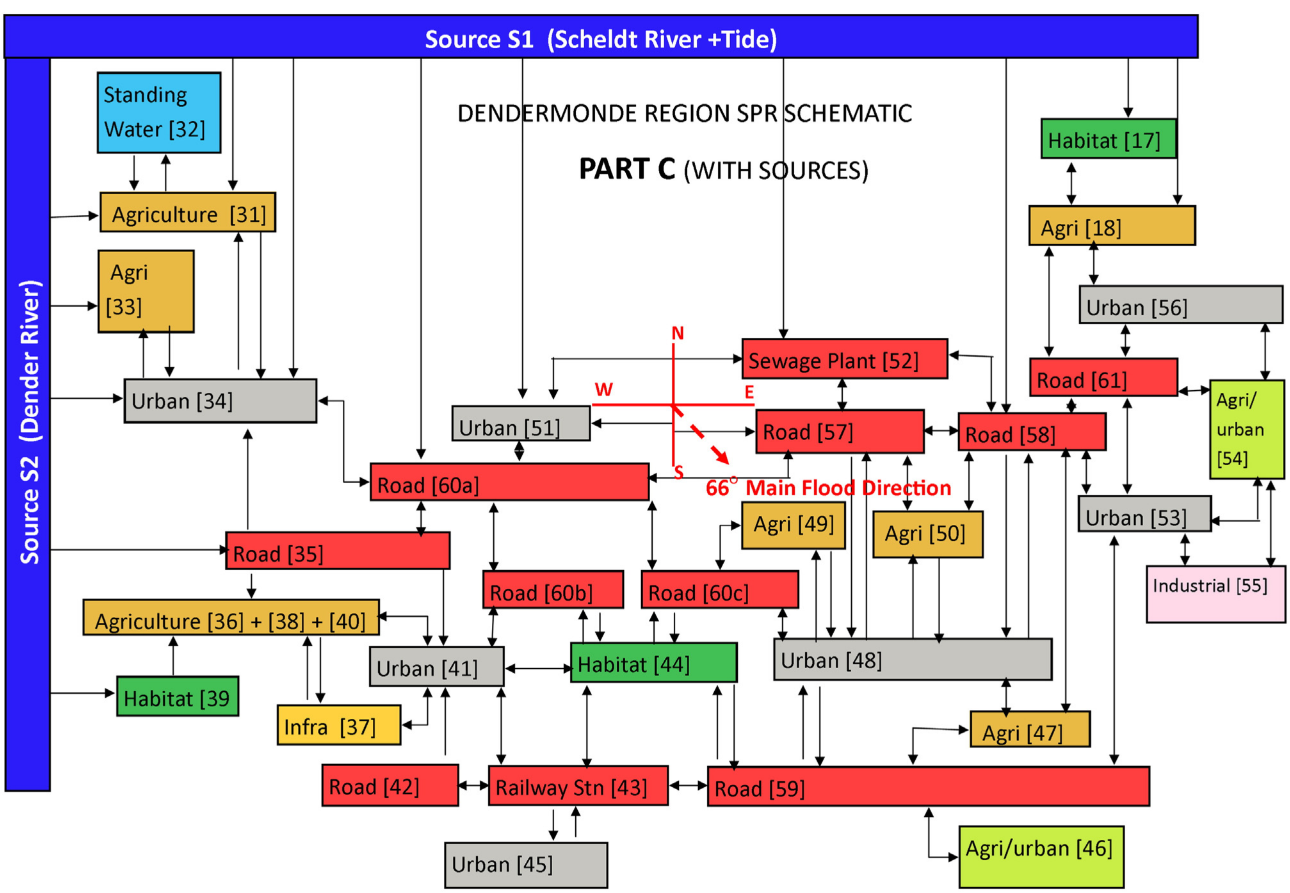

Fig. 4. Dendermonde city 2D SPR system diagram (red coordinates, arrows and text indicate critical flood direction). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

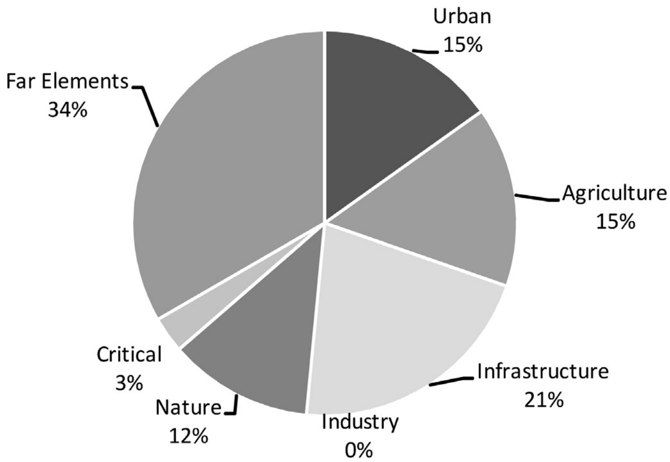

Fig. 5. Land-use distribution of exposed elements in the Dendermonde city floodplain from the 2D SPR (far elements are considered less exposed and their division in terms of land use is omitted).

elevations are less than that of Dendermonde city. All floodplain elements are directly connected to at least one flood source and are exposed on average to 2 flood sources, compared to the average of one source per element for Dendermonde city. The agriculture element in the north is seen as most critical since it forms the pathway to four out of the six floodplain elements. Adequate measures preventing the agricultural element 27 from acting as a flood pathway can therefore effectively serve as flood protection for the surrounding linked elements. From the DEM it can be seen that the road and urban areas are safe from flood levels less than 3 m. This 2D SPR was constructed relatively quickly and provides more insight than a basic bath-tub model, structuring understanding of the floodplain system and its relationship to the flood sources. This understanding can then inform and direct scenario selections in more detailed numerical inundation modeling.

4. The Elbe estuary

4.1. Current characteristics

The Elbe River reaches from the Karkonosze Mountains in the Czech Republic to the German Bight, North Sea. With a length of about 1094 km and a catchment area of 148,268 km^2 the Elbe River is one of the major rivers in Europe. The tidally influenced part, the Elbe estuary, extends from the tidal weir in Geesthacht to the North Sea and has a length of about 142 km (see Fig. 7).

The hydrodynamics in the German Bight dominate the hydrodynamic and morphodynamic processes in the Elbe estuary. The amplitudes and phases of the North Sea tides are heavily modified by the basin bathymetry and already get deformed by the reflection in the German Bight (Fickert and Strotmann, 2007; Nichols and Biggs, 1985). As a result of the interplay between the external forcing and the geometrical and topographical characteristics of the system, storm surges within an estuary exhibit a more complex behavior than at the open coastline. For the Elbe estuary the most important influences are those from the seaward boundary, e.g. tides, wind set-up, external surge, long-term sea level rise and to a lesser extent the freshwater runoff at the head of the estuary, mainly for the innermost part of the estuary between the weir and Hamburg.

The main characteristics of the estuary, which influence the development of a storm surge are:

- geometry of the estuary (length, depth, width, cross-sections) and roughness;
- civil engineering works (dikes, weirs, barriers, cutting off of tributaries);
- local modifications of the wind field.

4.2. History and functions

Diking, deepening and loss of intertidal area have led to a marked increase in maximum storm surge water levels along the estuary of 0.2 m to 1 m from the 1950s to the 1980s. This is accompanied by an increase

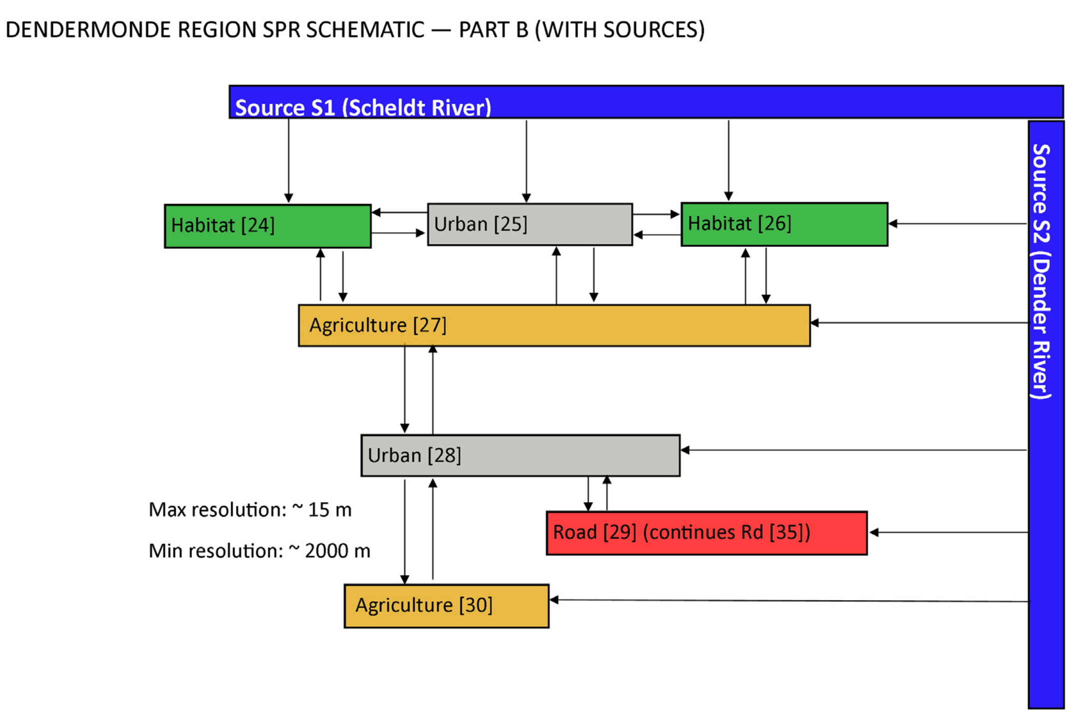

Fig. 6. 2D SPR for the floodplain to the south-west of the Scheldt-Dender confluence.

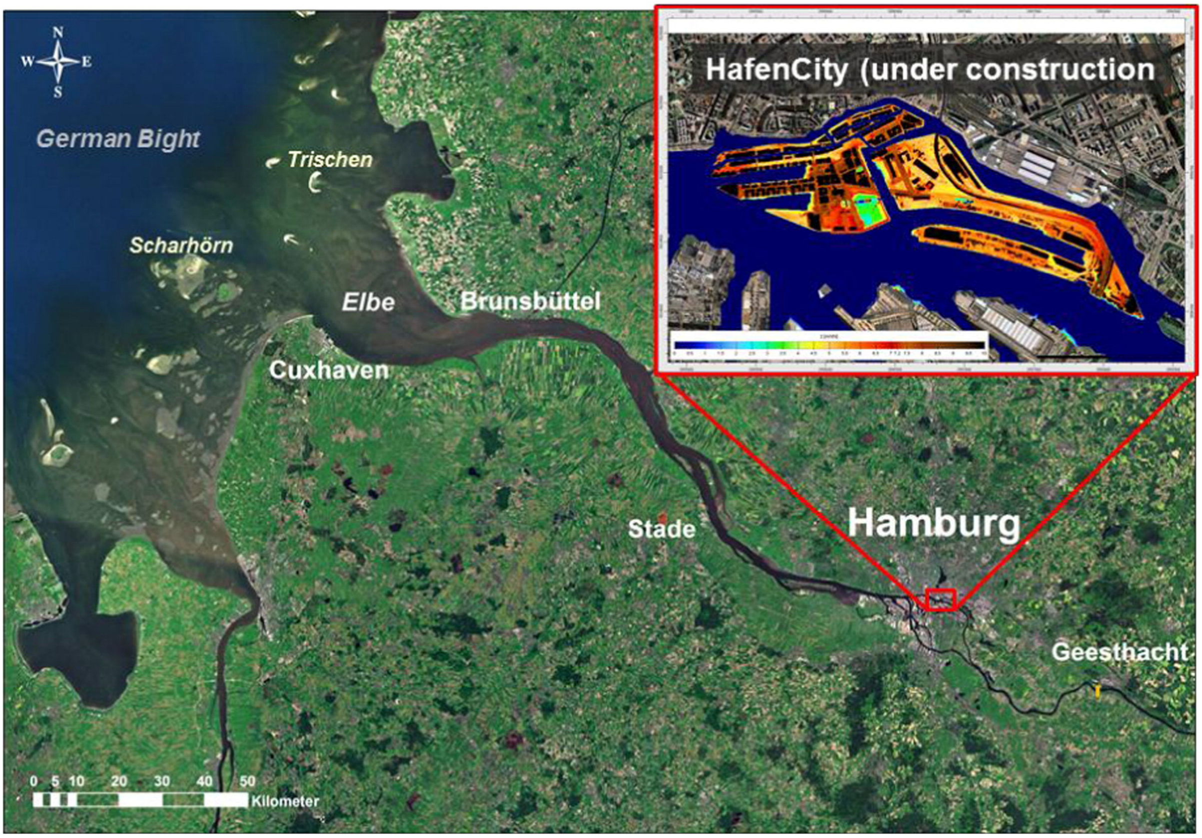

Fig. 7. Hamburg HafenCity within the Elbe estuary. (Source: Brockmann Consult, (c) 2003).

of the difference of maximum water levels in Hamburg and at the mouth of the estuary (Cuxhaven) by some 0.6 m and a decrease of propagation time of the storm surge from Cuxhaven to Hamburg by 1 h (Fickert and Strotmann, 2007). During the 1962 flood extended inundations occurred in Hamburg, after which massive investments in coastal defense infrastructure were made; dykes were raised to 7.20 m above German datum (NN (Normal Nul) = mean sea level around 1900). Due to advanced investigations and reviews dykes were raised further to a level between 8 m and 9.3 m above German datum beginning in the 1990s. Since 1962 several high storm surges occurred with heights between 5.5 m and 6.5 m above German datum, but only resulting in minor damages (Rohde, 1971).

The natural development of the estuary, including the adjustment to sea level rise, was interfered with by canalisation and the construction of controls such as dikes and barriers. Without such interference, the marshlands would have increased across the whole cross section. Dewatering the land behind the dikes led to consolidation. With the absence of sedimentation the hinterland ground level could not rise to match the rate of the constantly rising water level of the Elbe River.

The drainage of the hinterland has become more and more difficult. Since 1950 foreshore areas and flood plains of the Tidal Elbe River were reduced by 180 km^2. And with the construction of river barriers, the foreshore areas of the tributaries were also no longer available as flood plains. This meant that even more ecologically valuable intertidal areas had disappeared. Although some measures within the mouth of the estuary helped to restrict storm surges, Siefert and Havnoe (1988) showed that all diking measures together led to an increase of the maximum peak water level of almost half a meter at Hamburg during storm surges.

Apart from the historic development of coast protection and the cutting off of the tributaries by constructing barriers, the Tidal Elbe River has also seen large-scale changes as an important navigable waterway. As a result of the industrialization and the growing needs of a changing merchant fleet at the beginning of the 20th century, river engineering measures were necessary. These included the construction of training walls, alteration of cross-sections and the expansion of the ports of Hamburg, Cuxhaven, Brunsbüttel and Stade. These added to the natural changes in hydrodynamics over several centuries such as expanding channels, formation of new channels, migration of channels, sea level rise and those induced by geological and meteorological changes.

The hydrodynamic development of the tidal parameters is therefore characterized by an increase in the high water level and a decline of the low water level. This development is more significant further upstream. Along the estuary the maximum tidal amplitude is attained at the tide gage St. Pauli in Hamburg. The current avarage is about 3.6 m. 150 years ago the tidal range was about 2.0 m in St. Pauli (Fig. 8). The increase in tidal range is mostly due to the decline of the low water level making up about 2/3 of the variance. Note that this is different from the Scheldt estuary where the increase in tidal amplitude is mostly visible as an increase of the high water levels (see Section 3.2).

4.3. Fresh water input

The freshwater inflow from the catchment varies throughout the year, with maximum values generally in spring (>1500 m^3/s) and minimum values in summer or autumn (<300 m^3/s). The long-term mean of the freshwater run-off is about 709 m^3/s (Deutsches Gewässerkundliches Jahrbuch, 2008). Although there is a considerable variation in fresh water discharge [minimal discharge: 145 m^3/s (1947) and maximal discharge 3630 m^3/s (1940)], the effect on water-levels in the receptor area amounts to only some 10–15 cm, which is only 2.5% of the maximum storm surge contribution of 5.0 m.

4.4. Climate change scenarios

For the Elbe study site, only the IPCC scenario A1B is evaluated. Following Weisse et al. (in press) a sea level rise in the German Bight of

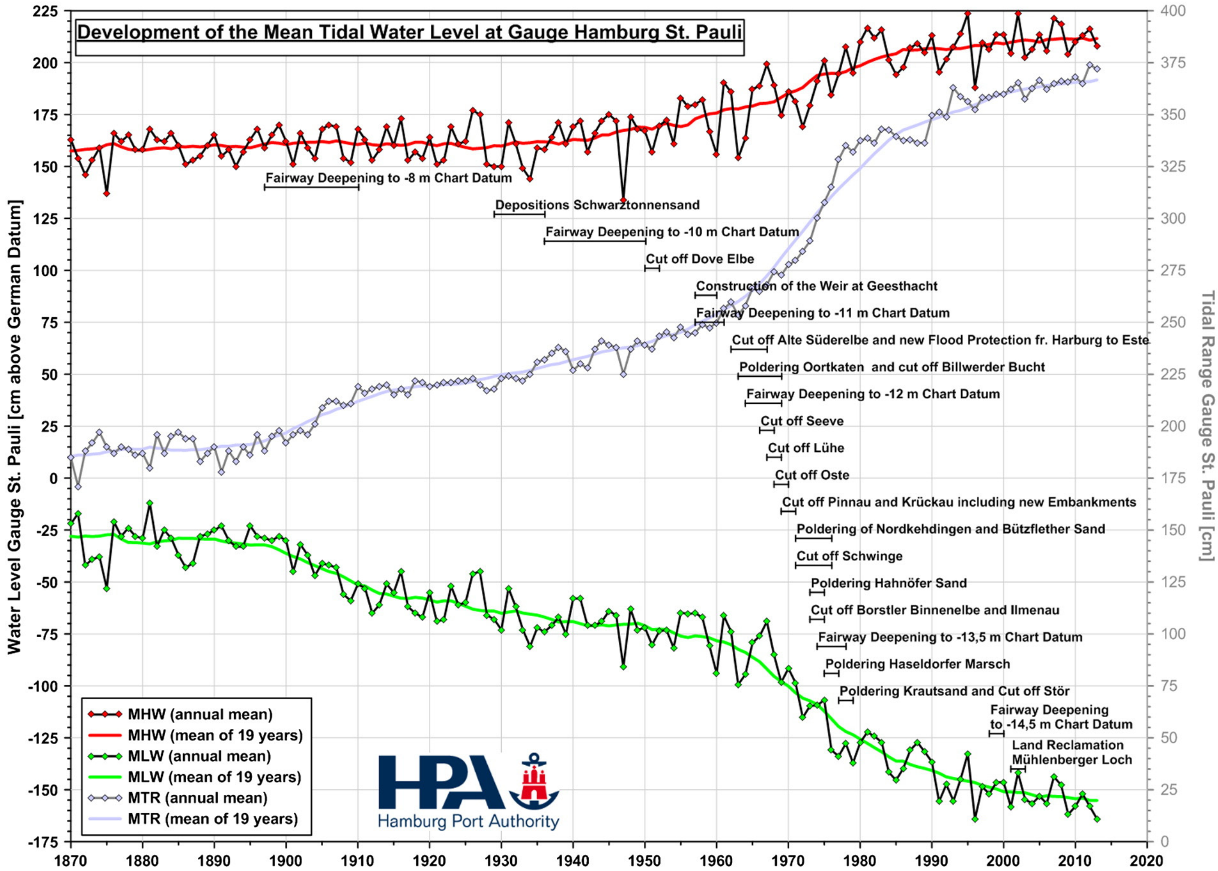

Fig. 8. Development of the mean high water and mean low water as annual values and 19-year-average values at the tide gage St. Pauli in Hamburg. Source: Hamburg Port Authority.

30 cm (2025), 50 cm (2055) and 90 cm (2085) is assumed. In this often used scenario there will be no significant changes (exceeding the natural variability) in waves and surges. The river flow will not significantly be altered, but its seasonality will change (higher flow in winter, lower in summer). For the receptor area of HafenCity in Hamburg only the sea-level rise will give a higher flood risk in the future. For this study site the 1/100 year event is considered as the extreme event.

4.5. Flood protection and hazards

Flood protections in the Elbe estuary are designed for a predicted storm surge in the year 2085 including climate changes (see Section 4.4). Since the receptor area HafenCity is located 100 km upstream of estuary mouth, it is quite sheltered from wave action and is mainly affected by storm surges. The HafenCity district is located between the main Elbe river and the public flood protection line along the river banks (Fig. 7) and its surface area is only a couple of square kilometers. The elevation of the area ranges from +4.4 m to +7.2 m above German datum, and is thus within the potential flooding area of the Elbe.

The conversion of the harbor areas into an inner city quarter is still in the construction phase and requires the development of structural and organizational solutions to protect people and buildings from flooding and also requires the listing of routes that enables the fire and rescue services to gain unlimited access in the event of flooding. Therefore it was decided to apply a new flood protection concept, putting new buildings on dwelling mounds well above the highest expected flood level. A previous study indicated a required minimum level of +7.5 m above German datum of the dwelling mound. The flood protection of single buildings is achieved by an ever increasing number of flood gates in the lower levels of the buildings. Providing this protection is left to the land owners.

The HafenCity site will be realized in development and building stages of various scales. The artificial dwelling mound solution is a suitable solution for phased development, because even single mounds provide complete protection. On the other hand not all buildings and street connections can be shifted onto an artificial dwelling mound, so that flood protection measures at single buildings have to be installed and inundations of streets and infrastructures cannot be avoided (Fig. 9).

4.6. Hydrodynamic and flood model

Flood maps for the HafenCity area were generated by using the numerical model FVCOM (Finite Volume Coastal and Ocean Model). FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model developed by joint efforts of UMASSD and WHOI. The details and results of the flood simulations are given in Ge et al. (2013). Two historical storm-induced flood events were simulated. The results showed a significant flooding situation under the strong storm process, such as the 1999 storm. The extent of flooding in HafenCity will be significantly increased under short-, middle- and long-term sea-level rise (SLR) scenarios of 0.3 m, 0.5 m, and 0.9 m. Most of the additional flooding occurs in areas that are already flooded under present conditions. These areas are intentionally exposed to flooding and consist of streets, low-lying canals, embankments and historical buildings, which cannot be shifted to the artificial dwelling mounds. The additional impacts of the mid- and long-term scenarios result in higher water depths in the already flooded areas. The relatively highest increase of flooded area results from a SLR of 0.3 m. The maximum flood water level in the 2085

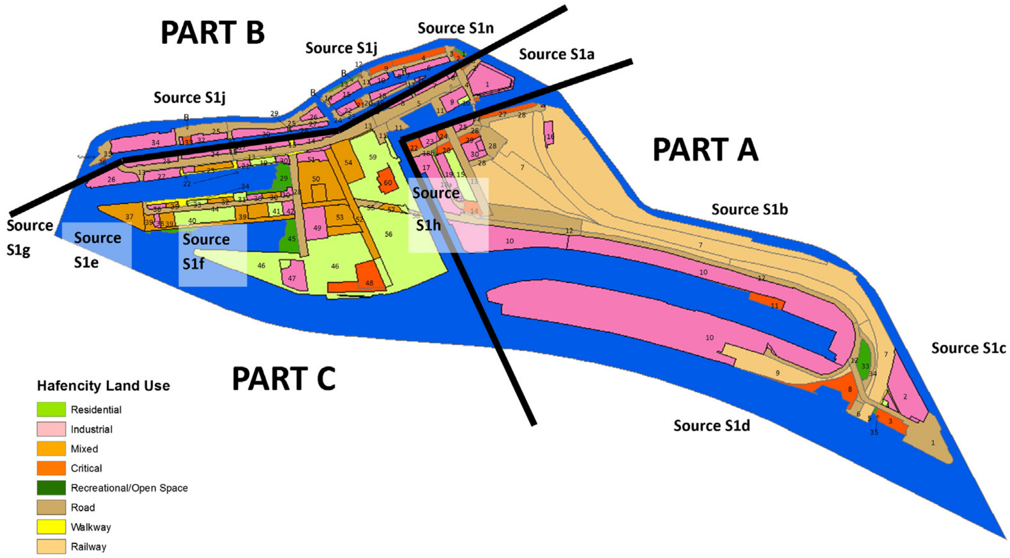

Fig. 9. 2D SPR Land-Use map for HafenCity area, based on the development scheme and land-use plan (year 2010).

scenario (SLR = 0.9 m) is 6.80 m above German datum. In summary, the peak flood levels will rise according to the respective SLR, while the flooded area will increase by 18% (2025), 34% (2055) and 54% (2085). The absolute values are 0.266 km^2 (present), 0.314 km^2 (2025), 0.356 km^2 (2055), and 0.410 km^2 (2085).

In contrast to the Dendermonde study site where a full 1D hydrodynamic model was used in combination with a conceptual river model and accompanied by a separate inundation model, the hydrodynamical modeling for the HafenCity study site was done with the 2D hydrodynamic model FVCOM. The main reason for this was the fact that 2D flooding maps for the different parts of HafenCity were required. The disadvantage of using this approach is that only a few selected events (here two strong storms) can be simulated because of computational demands.

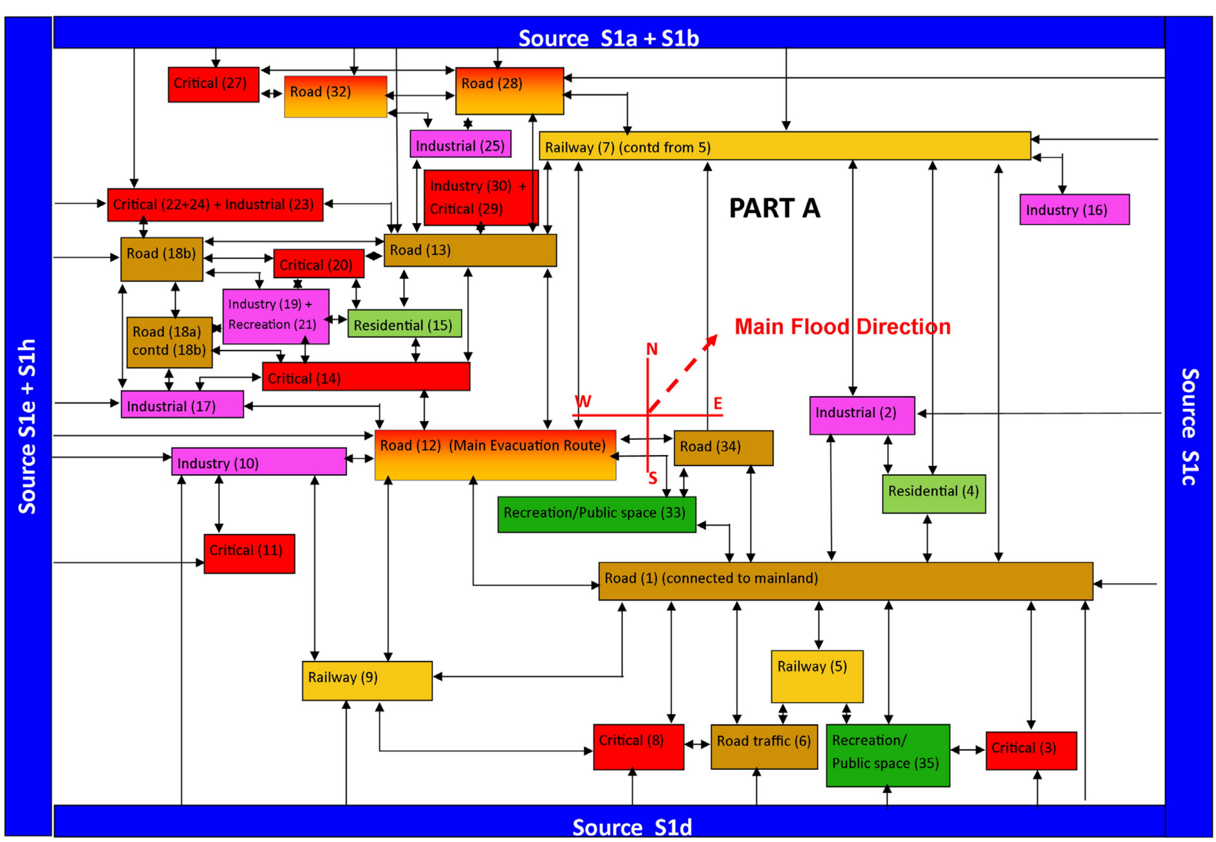

Fig. 10. SPR for Part A of the HafenCity area (right side island on land-use map, Fig. 9).

4.7. Schematic presentation of the SPR model

As already mentioned, the SPR approach focused on an area with readily available data and where flooding can occur. This led to the construction of a small-scale SPR model of the HafenCity, focusing on critical infrastructure and evacuation routes.

For this the HafenCity was divided into three parts (A, B and C — see Fig. 9). The SPR for the Part A is illustrated in Fig. 10. For the implementation of this schematic and linkage diagram, the following information was utilized:

- land-use map and development scheme of the year 2010;
- flood maps for present and future scenarios;
- defense and evacuation plans;
- relevant administration boundaries.

Roads, railways and evacuation routes are seen as critical for the flood safety of this part. Since the HafenCity region is still under construction, a validation of the flood model is not possible. The SPR model offers an alternative way of verifying flood model results based on expert opinion and local knowledge. For instance, the FVCOM numerical model results for Part A of the HafenCity does not indicate flooding in the region of Elements 2–4, though these are shown as linked to flooded zones across Element 1 (road/evacuation route). The FVCOM numerical model however does not resolve all small-scale canals and structures.

4.8. Findings

The HafenCity floodplain is unique amongst the three sites in that it is a series of connected islands. The SPR analysis for Part A of the HafenCity floodplain (Fig. 10) indicates an average of two flood sources for every exposed element and a maximum of four. The dominant direction of flooding is 56° (clockwise from North — red arrow in Fig. 10). In contrast the most vulnerable areas are affected by northern and eastern flood sources. Fig. 11 shows the distribution of land-uses across these elements.

Global (climate change, e.g. sea level rise) and local (civil engineering, e.g. flood defense, fairway adaptation) effects influence the flood risk in the Elbe estuary and the receptor area HafenCity in the same order of magnitude. This holds for the normal (mean) and storm surge conditions.

The SPR model of HafenCity highlights the sensitive receptors, which in some cases were not identified in the flood maps generated by the FVCOM numerical model. This reflects the fact that it is virtually impossible to include all the linkages and small-scale structures of the SPR model within the numerical model layout. The SPR approach can enable a better assessment of possible consequences of floods.

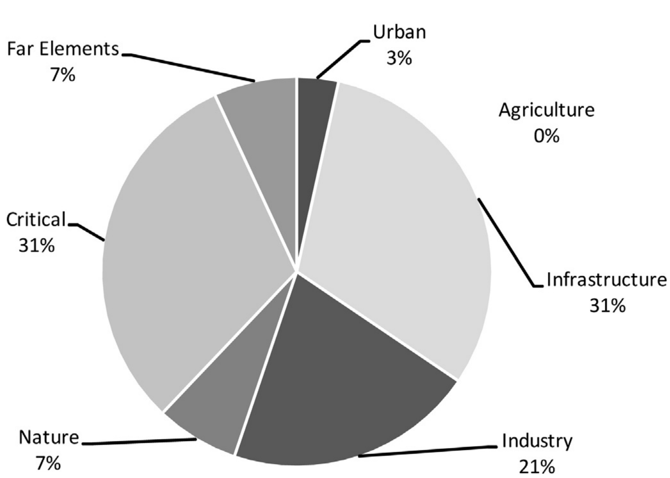

Fig. 11. Land-use distribution of exposed elements in HafenCity Part A (far elements are considered less exposed and division in terms of land use is omitted).

The sensitivity analysis of the receptor area can also be useful for the optimization of evacuation routes and plans. Moreover the results of the SPR analysis can be utilized in the next construction stages of HafenCity.

5. The Gironde estuary

5.1. Current characteristics

The Gironde is the largest estuary in Europe with a surface area of 635 km^2. Saline water flows upstream up to the confluence of the two rivers Garonne and Dordogne near Ambès. The distance from there to the mouth of the estuary is about 75 km. However, tidal waves are felt farther upstream, up to 170 km from the mouth, near La Réole (Fig. 12).

Due to the funnel shape of the estuary, the tidal amplitude increases when it propagates towards the continent. For average tides, the amplitude is about 3.1 m at the mouth and goes up to 4.2 m in Bordeaux before decreasing again. The wave is strongly asymmetric, all the more so upstream, with the ebb tide lasting for about 2/3 of the semi-diurnal period.

5.2. History and functions

The risk of flooding has always been a major concern of authorities along the estuary. Champion (1862) show that it was the case at least since the 13th century with several consecutive floods of the Garonne and Dordogne in 1212, 1310, 1425, 1523, 1536, and 1542. The most damaging flood occurred in April 1770, when about 24,000 km^2 were covered by water along the Garonne and Gironde, causing enormous damage in the city of Bordeaux. Special aid was offered by the king to help in the rehabilitation of the city. From this point, measures were taken to limit the consequences of flooding. However, they did not prevent new strong floods to occur in 1835 and in the following years, 1855 and 1856 and above all 1875 when 500 people lost their lives. In 1930 again, floods caused the destruction of 1000 houses and more than 300 human lives were claimed. In the last decades, three main events are burnt in the memories of people: one in December 1981 mainly due to strong river discharges in combination with high tidal amplitude, then the Lothar and Martin storms in 1999 and most recently the storm Xynthia in 2010.

Repetitive floods led to an early adoption of preventive policies and protection measures. However, previous experience show that those policies still lack coordination at the scale of the estuary (de Vries et al., 2010).

Contrary to other European estuaries, the estuary of Gironde still relies very heavily on its natural functioning with a unique ecosystem that allows for the growth of special species of fishes which are not found elsewhere in France, like the European sea sturgeon. Those species are threatened today by the contamination of river water and by strong anthropogenic pressure. Fishing is commonly adopted along the estuary and it contributes to 6% of the total fishing activity in France. A large part of the coastal area is dedicated to vineyards. Industry is quite well developed upstream of the estuary, with oil refineries and chemical industries near Ambès and a nuclear power plant near Blaye. Activities in the tertiary sector are well developed near and in Bordeaux.

The morphodynamic evolution of the bottom of the estuary which is responsible for the creation of new islands and for the displacement of current ones, has made navigation difficult, but this did not prevent Bordeaux from being the first French harbor until the nineteenth century. Today, two channels are dredged to allow for the arrival of ships in Bordeaux, Pauillac and Verdon.

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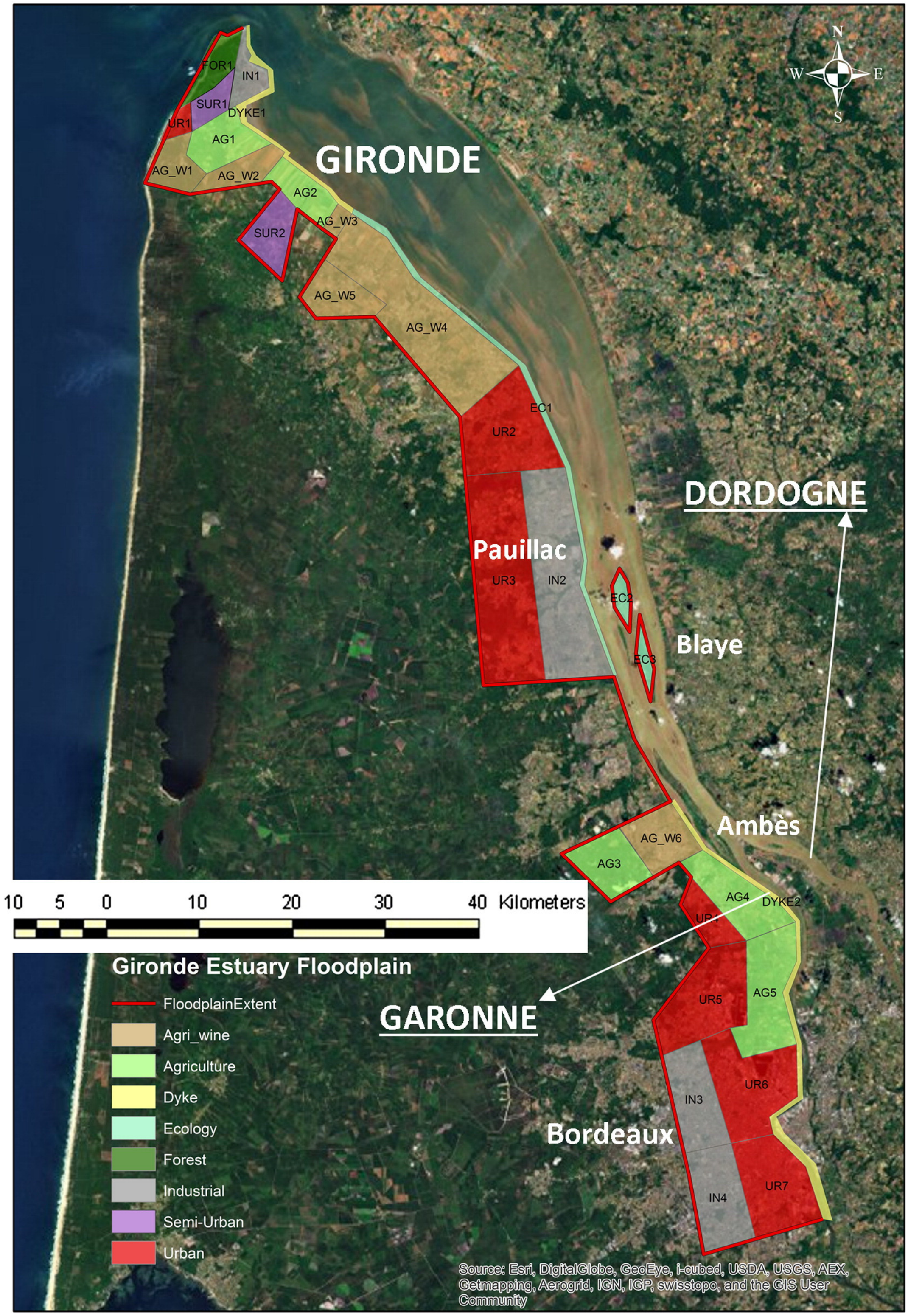

Fig. 12. View on the Gironde estuary. Land use is superimposed for the left bank only.

5.3. Fresh water input

At the mouth of the estuary, the total oscillating volume during a tide is about 1.75 billion m^3 and it decreases according to an exponential law with respect to the distance to the mouth (Mignot, 1969). At the confluence, some 75 km upstream, this is reduced to 80 million m^3 among which 52 million m^3flow to the Garonne and 28 million m^3 flow to the Dordogne. In one year, it can be estimated that about 900 billion m^3 enter in the estuary at the mouth, and about 35 billion m^3 flow through a transverse section in Bordeaux.

In comparison, the average combined river discharges of Garonne and Dordogne is 30 billion m^3per year at the confluence in Ambès. At

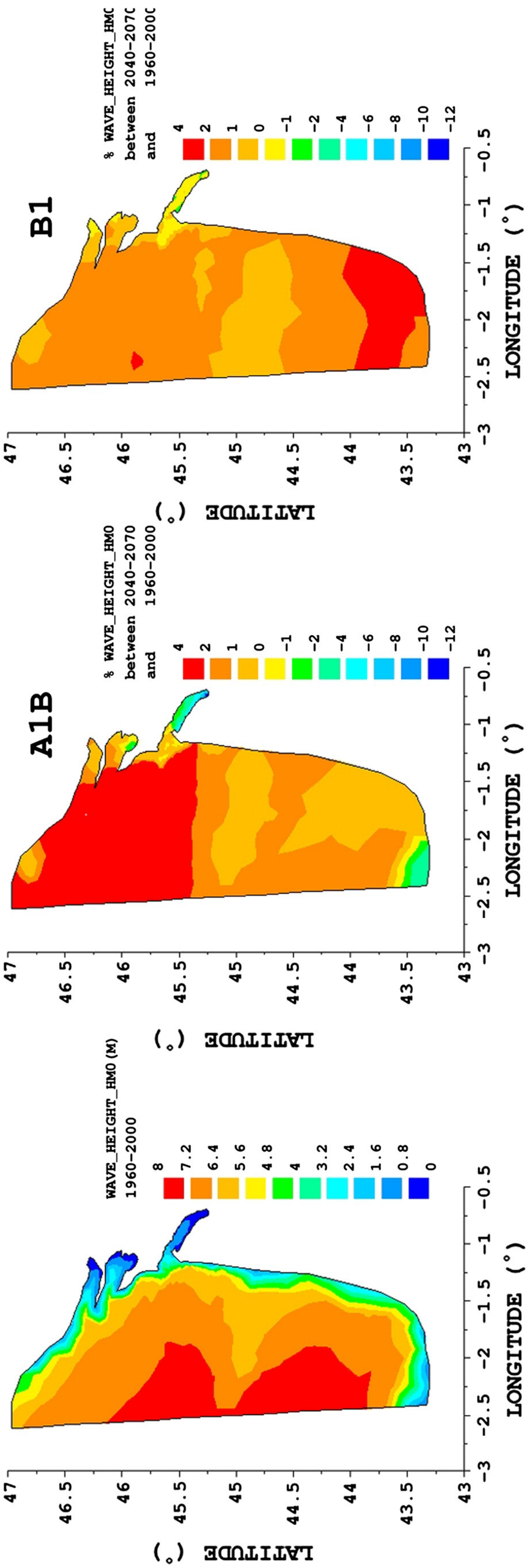

Fig. 13. 100-year return period wave heights for present conditions, and change in % for the future period 2040–2070 under climate change scenarios A1B and B1.

this point, the river discharge is in the same range of value as the tidal oscillating volume. The discharge of Garonne may exceptionally reach a value of 8000 to 9000 m^3/s, but usually does not exceed 4000 m^3/s with an average discharge of 620 m^3/s. In summer, low flows may lead to discharges under 200 m^3/s. Dordogne's discharges are lower and seldom exceed 2000 m^3/s with a yearly average value of 270 m^3/s in Bergerac.

The above figures show that the discharges of Garonne and Dordogne rivers contribute in a substantial way to the level of flood risk along the estuary, especially upstream from the confluence of the two rivers in Ambès. During an interview at the beginning of the Theseus project, the chief fireman of the Gironde department in Bordeaux indeed stated that the risk is due to the addition of four components: high storm surges, high tides, strong winds and high river discharges. Major events in the last three decades resulted from the combination of three of those factors, but an extreme event combining all four causes can still be expected.

5.4. Climate change scenarios

Climate change is expected to have an impact on the hydraulic loads on the mouth of the estuary. One of its main consequences will be a rise in the average level of sea. According to the French office for studies on climate change (ONERC, 2010), three scenarios have to be considered: an optimistic one with a sea level rise of 0.40 m, a pessimistic one with a rise of 0.60 cm, and an extreme one with a rise of 1 m, all rises by the end of the century.

Waves and storm surges may also vary due to a change in the surface winds on the Atlantic Ocean. Waves only have an influence on the rather rural territories near the mouth of the estuary. For this source, two hydraulic models were built using the Tomawac software, one over the full Gascogne Golfe, the other centered on the Gironde estuary (Morellato, 2010). Its resolution is between 1° offshore and 0.25° nearshore. The model was forced with winds from both a global climate model (ECHAM5) and the European one provided through the Theseus

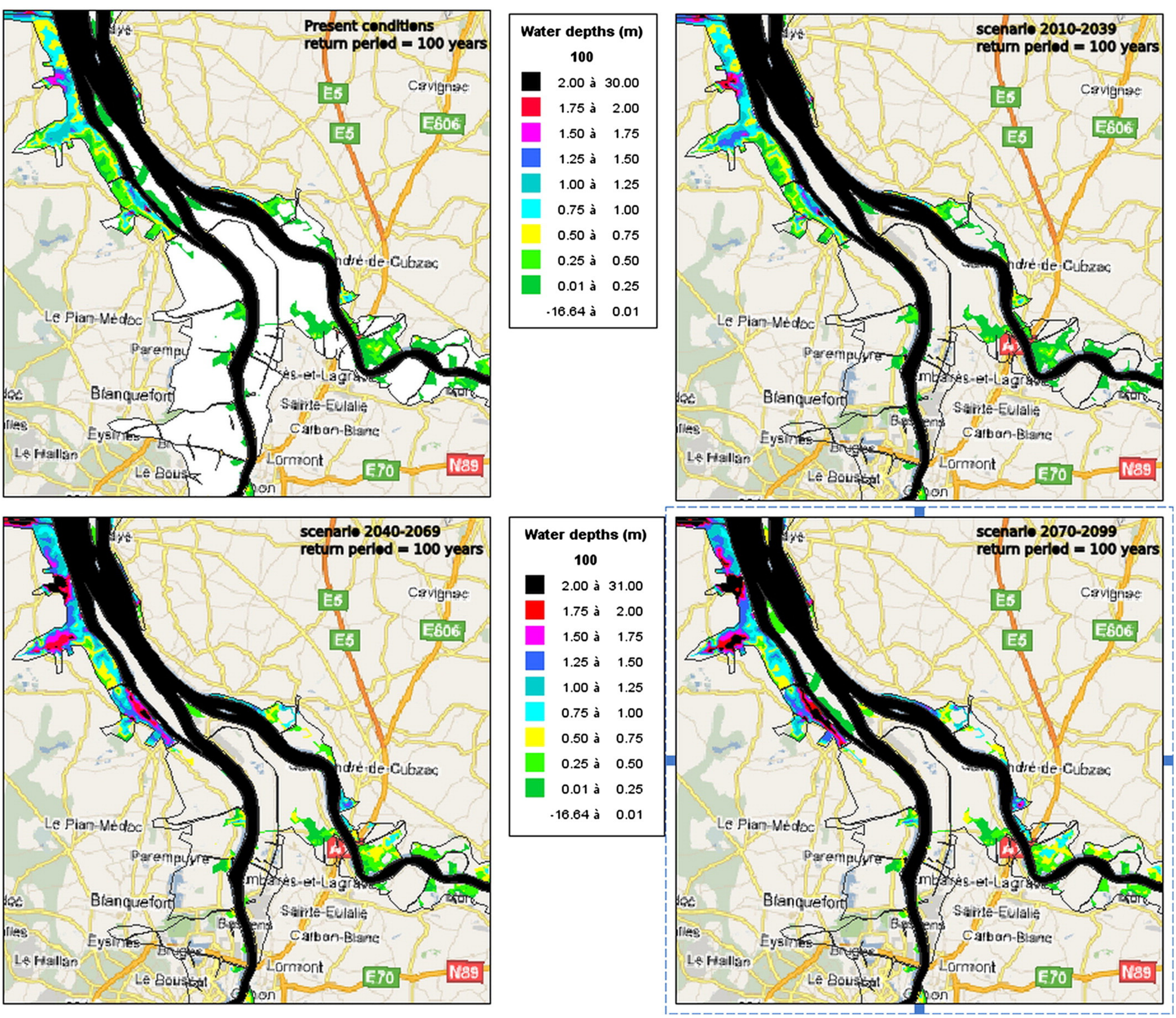

Fig. 14. Water levels for 100-year return period flood, near the confluence of the two rivers, for present conditions and three future time slices.

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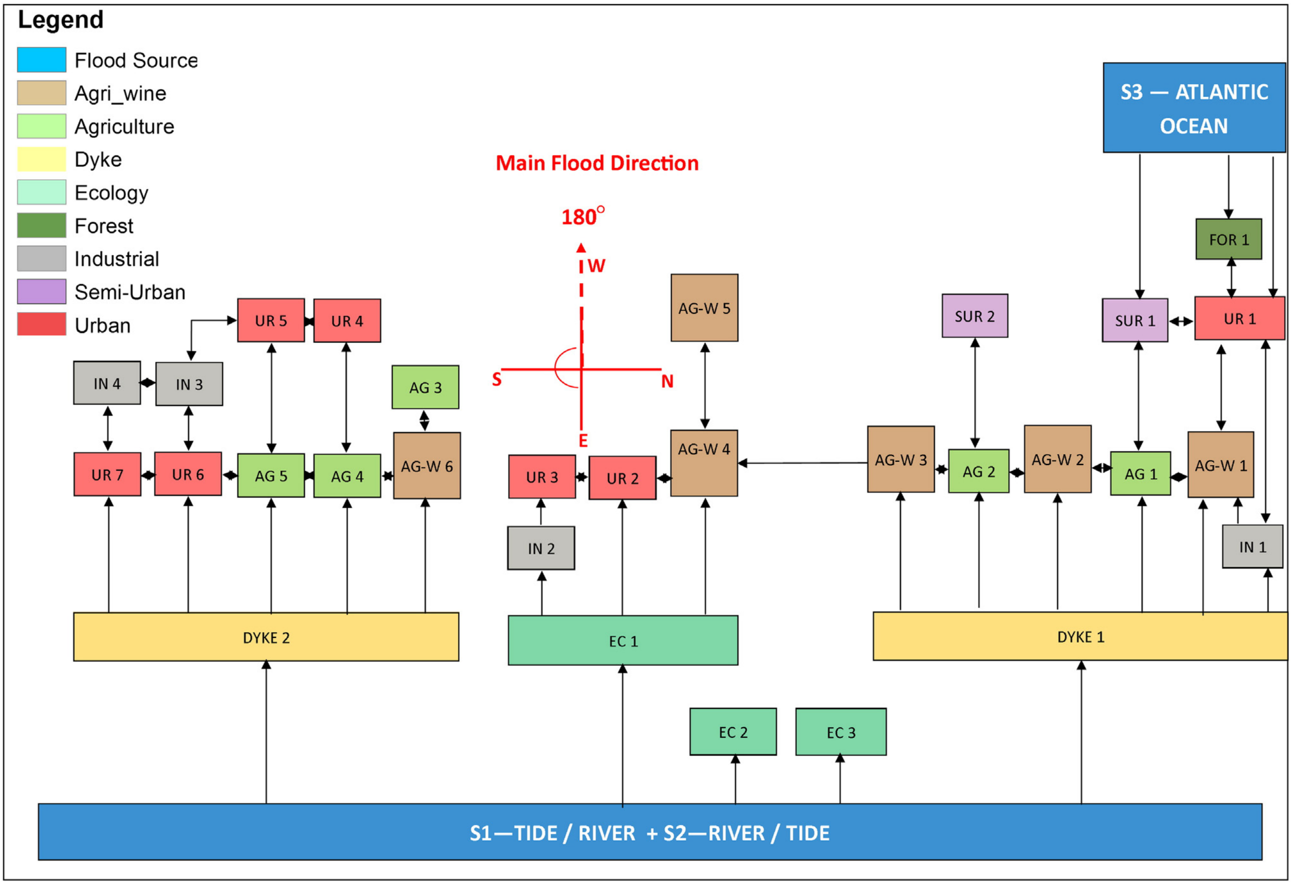

Fig. 15. Large-scale SPR for Gironde estuary.

project (Weisse et al., in press). Simulations were made for two time slices: 1960–2000 to calibrate the model, and 2001–2100 to evaluate how conditions will change. For the future period, two global climate change scenarios from IPCC were used: A1B and B1. A1B has a more economic focus with a balance between fossil and non-fossil energy resources, while B1 has a more environmental focus. The results, partially presented in Fig. 13, show that the average wave height tends to decrease until 2100, but variations are generally slight (between −10% and −4%). The number of storms decreases a little while extreme wave heights slightly increase (up to 3% for A1B scenario, 1% for B1 scenario). These changes are quite small but seasonal analysis shows larger variations, with a 10% increase of wave heights during winter and a 25% decrease during summer.

Storm surges were correlated with local wind data near the mouth of the estuary through a simple relation where the storm surge is a sum of three terms, one proportional to the square velocity of the wind, the second proportional to the pressure, and a third constant term (Laborie et al., 2012).

The coefficients of this correlation were calculated on a set of 10 selected extreme events with an average duration of two weeks each. The correlation function was then run for the next century, using as input the CLM/SGA database for future winds (Weisse et al., in press). Those calculations led to the conclusion that extreme storm surges generally decrease in the future. 50 and 100-year return period surges decrease by about 5 cm by 2050 and 8 cm by 2100.

There is more uncertainty about the change in river discharges in the future. In the absence of more detailed information, the discharges of Garonne and Dordogne were considered stationary during the next century in the Theseus risk assessment.

5.5. Flood protection and hazards

According to de Vries et al. (2010), dike management is very fragmented along the estuary with for example more than 400 owners for a stretch of 20 km. In total, there are 433 km of dikes with different levels of protection on the study site. SMIDDEST, a syndicate of municipalities and local authorities, was established in 2001 with as main aim building a consensual strategy for risk mitigation shared by all stakeholders on the estuary. One of the first actions of SMIDDEST supported

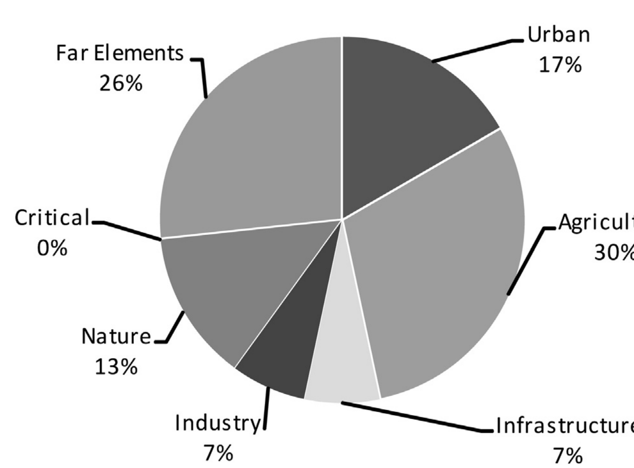

Fig. 16. Relative distribution of land-uses of exposed elements in Gironde FP (far elements are considered less exposed and division in terms of land use is omitted).

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by national government was the development of a large flood database on the Gironde (RIG), including a risk assessment and a numerical model of the estuary. This tool served as a basis for the preparation of the action plan for the prevention of flooding (PAPI) which is a first co-ordinated policy for the reduction of the risk, including structural mitigation measures and non-structural options to limit the vulnerability of the exposed areas. Now, 32% of dikes along the estuary are managed by SMIDDEST and other syndicates of municipalities in a more homogeneous way (de Vries et al., 2010).

(Un)fortunately, recent events and especially the Xynthia storm raised awareness of the need for a joint approach of risk mitigation. In the aftermath of this Xynthia event, a global inspection of the state of all dikes along the estuary was carried out. This showed that the state of dikes varies a lot, with about 50% of them in good condition, 30% in moderately-good condition and 20% in poor condition.

5.6. Hydrodynamic and flood model

The numerical model of the estuary developed in the framework of the RIG (see above) was used to delineate the extent of extreme floods in the estuary for present and future conditions. The model is a 2D shallow-water model based on the Télémac software. It was adapted to take into account dikes overflowing and to simulate the flood dynamics in the flood plain. It is however assumed that existing dikes do not break during a flood event. The model was calibrated over real observations between 1960 and 2000, and run between 2000 and 2100 using as input the hydraulic loads established in the previous stage of the project (see climate change section above).

Flood extents corresponding to different return periods between 1 year and 100 years were calculated for three future periods (2011–2040, 2041–2070 and 2071–2100) by applying a peak-over-threshold statistical analysis on the raw results of the simulation for each of the 13,621 nodes of the finite-element model. Outside the river bed, a threshold of 1 cm was used, so that an event is qualified as extreme as soon as there actually is water in the floodplain. A Gumbel distribution was used to fit the number of occurrences of extreme flood events.

The Gironde Estuary is a very large area. Water levels corresponding to return periods of 2, 5, 10, 20, 50 and 100 years have been mapped for three specific sites of interest. Those are located at the maritime frontier of the model in the neighborhood of Le Verdon, at the confluence between Dordogne and Garonne rivers and in Bordeaux and its surroundings. As an example the extent of the 100 year return period flood is illustrated in Fig. 14.

5.7. Schematic presentation of the SPR approach

The Gironde is an example of a much larger-scale application. In Fig. 12 the large scale land use has construction of the SPR model (Fig. 15). Only the left bank is shown here. It covers the length of the Gironde estuary from the mouth to the city of Bordeaux and this is mapped in the SPR model with the estuary as the main source of flooding. Historic coastal recession data and shoreline models identify a potential breach location on the Atlantic Ocean side of the floodplain. This is mapped as an additional source of flooding which becomes more likely as sea levels rise. The large-scale SPR (Fig. 15) is used to identify the regions threatened by the potential breach. In addition, a detailed small-scale model SPR was developed (not shown) using existing local knowledge of designated flood pathways to describe the floodplain in case of the Atlantic Ocean breach. This full model has 97 receptors, 5 sources, and more than 200 pathways: it was used as the basis of a Decision Support System as explained below.

In the large scale model, the sources are the ocean and the two rivers. The ocean has two types of impacts: it can lead to the direct flooding of the areas west of the estuary (source S3), but tides and storm surges that propagate into the estuary are secondary sources (S1 and S2). These sources are always combined with the one originating from the river discharges. The influence of tides is predominantly downstream while the influence of river discharges is more important upstream. Waves are only important right at the mouth of the estuary. Further upstream, only water levels are involved in the flooding processes.

5.8. Findings

Analysis of the large-scale 2D SPR indicates an average of one flood source per exposed element though the maximum is three. What is most distinct in Fig. 15 is that the predominant flood direction is directly westward due to the dominance of the two riverine flood sources. However elements IN 1, AG-W 1 and AG 1 at the downstream end are affected by all 3 sources. Fig. 16 indicates the relative land-use distribution of the exposed elements.

The SPR approach showed the variety of land-use configurations that are exposed to flooding in the estuary. It helped to identify the critical elements that were threatened, which are located in the city of Bordeaux and in the industrial areas north of Bordeaux near Ambès. Moreover, it showed those sections that are exposed to three sources. Local authorities therefore might need to prepare for a catastrophic event stronger than the ones they have encountered so far, resulting from the combination of the three sources. The SPR approach identified the elements at stake. These should get the highest priority in the risk mitigation policies.

The Gironde is one of the pilot sites of the Theseus project for the implementation of the decision-support system (DSS), a software aimed at informing coastal managers and decision makers about the costs and consequences of different scenarios of risk mitigation, including structural protection measures and socio-economic policies (Zanuttigh et al., 2013). The SPR approach developed here is used to define the elements in the DSS. For each receptor unit in the SPR approach, a cost is associated to a flood event and is made of three components: a monetary cost of material damages, the number of lives lost and an environmental value index variation. Pathways are implemented in the software through transfer functions which establish a relation between the source (usually hydraulic variables such as water levels, water velocities, specific wave heights,…) and the receptor (e.g. aggregated flood depth due to overtopping).

A mitigation measure comprises a list of possible actions taken by the local authorities which have an impact either on the pathways in the SPR model (mostly for structural measures), or on the receptor units (mainly socio-economic policies). The source inputs remain the same, whatever the measures.

The DSS allows a comparison of different mitigation measures. In the Gironde area, the mitigation measures tested are both measures already proposed by the local authorities in the framework of the action plan for the prevention of flooding (PAPI) (usually raising the level of dikes or building new dikes), and new innovative measures using the technologies developed by the Theseus project (wave energy converters, reinforcement of dikes, managed realignment).

6. Discussion and conclusions

All three SPRs focus on the sources of flooding when representing the floodplain. The 2D SPRs show that the sites have potential flood sources, and therefore flood pathways, coming from multiple directions. Though all three sites are estuarine coastal regions, the nature of the considered flood sources and the subsequent risk analyses differ greatly. Flood sources along the Scheldt combine extreme surge and river runoff and these are considered also in the future climate scenarios. On the other hand, the Gironde estuary SPR showed the potential emergence of a third distinct flood source from the open ocean which has not yet been observed in past flood events, but becomes more likely as sea levels rise. In the Elbe estuary, the SPR identifies the HafenCity area as vulnerable due to the nature of the existing defenses and the

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consequences of a potential flood event. All three estuaries are therefore seen to be distinct in their characteristics and in the nature and purpose of their flood risk assessments. Application of the SPR to these sites provided a common, structured methodology within which users can frame their flood risk analyses and models.

In all study sites emphasis has been on probability of flooding without consideration of dike failure. i.e. it is assumed that dikes do not fail. The methodology can be extended to include dike failure provided that probabilistic information for dike failure is available.

Although the sites are relatively close in planetary terms, it proved impossible in practice to homogenize assumption on climate change and sea level rise. The scenarios used for assessing the impact of climate change but also the tools used to work out the hydrodynamics differed from site to site. The main reason for this is that the study sites are quite different in concept, history and development of plans for protection of coastal flooding.

For the Dendermonde site use could be made of full hydrodynamic models and simpler conceptual models for flood propagation in the river basins of the Scheldt and Dender. Conceptual models are calibrated to the full hydrodynamic models and allow for fast calculations of different scenarios. For the Elbe river, a full 2D hydrodynamic model has been used to study the details of flood propagation in HafenCity. Similarly the experience with the TELEMAC hydrodynamic software and the TOMAWAC wave model, made it logical to choose these models for flood and wave impact studies in the Gironde estuary.

The expected effect of sea level rise is for all sites considered as the most important source of worry for the future. In all sites a change in tidal propagation along the river is expected that can be attributed to sea level rise and expected changes in storminess and surge elevations. Changes in tidal propagation are clearly visible from historic records where both sea level rise and deepening for navigation purposes, have increased the tidal range considerably, especially in the Elbe and the Scheldt estuary. Due to the geometry of the estuary the dominant effect is an increase of the high water levels along the Scheldt and a decrease of the low water levels along the Elbe.

The application and analysis of the 2D SPR methodology revealed in each of the study sites additional information relevant to flood risk evaluation. For the Scheldt estuary complete coastal flood protection plans have been developed and are expected to provide adequate protection for the next few decades at least. The Dendermonde area falls under the Sigma plan which is a comprehensive flood defense plan including a social cost benefit analysis. Nevertheless the Scheldt SPR exercise brought insight and structure to the flood risk analysis which is shaped by a complex interplay and impact of downstream (coastal) and upstream (inland) controlled sources. For the Dendermonde study site, the climate related expected changes in rainfall-runoff and in downstream surge levels will have a combined impact on the area of Dendermonde. The SPR approach ensured that basic assumptions about the floodplain are made explicit. The HafenCity floodplain is unique among the three sites in that even though the flood sources are estuarine, the floodplain itself is an island. The SPR analysis mapped some elements as potentially flooded, which were not identified in the 2D flood model. This is reflected in the greater number of flood sources (an average of two per exposed element with a maximum of four). The land-use pie chart for this floodplain not only showed the expected high degree of urbanization but also a large percentage of critical elements including evacuation routes exposed to the flood sources. In contrast in the Gironde case study, the SPR was very effective in mapping different designated and non-designated flood pathways as a result of estuary flooding and Atlantic Ocean breach succinctly. The SPR method proved to be a quick and effective way of combining and mapping diverse information.

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References

Champion, M., 1862. Les inondations en France du VIème siècle à nos jours. Tome IV (in French).

Deutsches Gewässerkundliches Jahrbuch, 2008. Elbegebiet, Teil III. Hamburg Port Authority, Freie und Hansestadt Hamburg.

de Vries, W., Steendam, G.J., van der Nat, A., Graaff, H., Kloosterboer, H., 2010. Assessment of current policy, management and planning strategy and durability of strategies on coastal defences. Theseus Deliverable ID 1.2.

Evans, E., Ashely, R., Hall, J., Penning-Rowsell, E., Sayers, P., Thorne, C., Watkinson, A., 2004. Foresight Future Flooding, Volume I and Volume II. Office of Science and Technology, London.

Fickert, M., Strotmann, T., 2007. Hydrodynamische Entwicklung der Tideelbe. In: Gönnert, G., Pflüger, B., Bremer, J.-A. (Eds.), Von der Geoarchäologie über die Küstendynamik zum Küstenzonenmanagement. Coastline Reports 90928-2734. ISBN: 978-3-9811839-1-7, pp. 59–68 (in German).

Ge, J., Kappenberg, J., Much, D., Ding, P., Ohle, N., Chen, Z., 2013. Simulating flooding maps over HafenCity under present and sea level rise scenarios. J. Flood Risk Manag. http://dx.doi.org/10.1111/jfr3.12054.

Grabemann, I., Weisse, R., 2008. Climate change impact on extreme wave conditions in the North Sea: an ensemble study. Ocean Dyn. 58 (3–4), 199–212.

Laborie, V., Hissel, F., Sergent, P., 2012. Evolution de l'emprise des zones inondables de l'estuaire de la Gironde sous l'influence du changement climatique. Journées Nationales Génie Civil Génie Côtier, Cherbourg (in French).

Lowe, J.A., Howard, T.P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., Bradley, S., 2009. UK Climate Projections Science Report: Marine and Coastal Projections. Met Office Hadley Centre, Exeter.

LTV 2030. http://www.vnsc.eu/uploads/2012/01/ltv-schelde-estuarium-18-januari-2001.pdf (last consulted 09/30/2013).

Mignot, C., 1969. Estuaire de la Gironde, synthèse des phénomènes naturels. Tech. Rep. Laboratoire central d'hydraulique de France (in French).

Morellato, D., 2010. Waves and climate change — report 2: wave modeling in the Gironde estuary from 1960 to 2100. Tech. Report CETMEF.

Narayan, S., Hanson, S., Nicholls, R.J., Clarke, D., Willems, P., Ntegeka, V., Monbaliu, J., 2012. A holistic model for coastal flooding using system diagrams and the Source–Pathway–Receptor (SPR) concept. Nat. Hazards Earth Syst. Sci. 12, 1431–1439.

Narayan, S., Nicholls, R.J., Clarke, D., Hanson, S., Reeve, D., Horillo-Caraballo, J., le Cozannet, G., Hissel, F., Kowalska, B., Parda, R., Willems, P., Ohle, N., Zanuttigh, B., Losada, I., Ge, J., Trifonova, E., Penning-Rowsell, E., Vanderlinden, J.P., 2014. Evaluating the 2D Source–Pathway–Receptor model for flood risk assessment. Coast. Eng. (this volume).

Nichols, M.M., Biggs, R.B., 1985. Estuaries. In: Davis, R.A. (Ed.), Coastal Sedimentary Environments. Springer, New York, pp. 77–187.

Ntegeka, V., Decloedt, L.-C., Willems, P., Monbaliu, J., 2012. Quantifying the impact of climate change from inland, coastal and surface conditions. In: Klijn, F., Schweckendiek, T. (Eds.), Comprehensive Flood Risk Management — Research for Policy and Practise. Proceedings of the 2nd European Conference on Flood Risk Management FLOODRisk 2012, Rotterdam, The Netherlands, 19-23 November 2012. CRC Press, Taylor & Francis Group, Leiden, The Netherlands. ISBN: 978-0-415-62144-1, pp. 103–111.

ONERC, 2010. Synthèse n°2: Prise en compte de l'élévation du niveau de la mer en vue de l'estimation des impacts du changement climatique et des mesures d'adaptation possibles (in French).

Pieters, T., Dillingh, D., Graveland, J., 2005. Het Scheldegetij. Werkdocument RIKZ/ZDA/2005.801. (80 pp., in Dutch http://www.vliz.be/en/imis?module=ref&refid=144261&pp=print).

Rohde, H., 1971. Die Elbe als Schiffahrtsstraße, Mitteilungen des Franzius-Instituts der Technischen Universität Hannover, Heft 36 (in German).

Siefert, W., Havnoe, K., 1988. Einfluß von Baumaßnahmen in und an der Tideelbe auf die Höhe hoher Sturmfluten. Die Küste. Archive for Research and Technology on the North Sea and Baltic Coast, Heft 47, pp. 51–101 (in German).

Van Rijn, 2010. Tidal Phenomena in the Scheldt Estuary. Deltares Ref. 1202016-000-ZKS-001.

Van Rijn, 2011. Tidal Phenomena in the Scheldt Estuary, Part 2. Deltares Ref. 1204410-000-ZKS-001.

VNSC, 2010. Safety against flooding. Indicators for the Scheldt estuary. Commissioned by the Maritime Access Division, project group EcoWaMorSe, Flemish–Dutch Scheldt Commission. VLIZ Information Sheets, 219. Flanders Marine Institute (VLIZ), Oostende (12 pp., http://www.scheldemonitor.org/imis.php?module=ref&refid=201569).

VNSC, 2013. Ministerie van Infrastructuur en Milieu, Rijkswaterstaat Zeeland, Uitvoerend secretariaat van de Vlaams-Nederlandse Scheldecommissie, 2013. T2009-Rapport Schelde Estuarium (T2009 Report Scheldt Estuary), p. 500 (+ appendices available http://www.vnsc.eu/organisatie/werkgroepen/onderzoek-en-monitoring/voortgang/projectgroep-evaluatie-en-rapportage; main report http://www.vnsc.eu/uploads/2013/08/t2009-rapport-schelde-estuarium-22-augustus-2013-077257117-va.pdf (last consulted on 09/18/2013) (in Dutch)).

Weisse, R., Bellafiore, D., Menendez, M., Mendez, F., Nicholls, R., Umgiesser, G., Willems, P., 2014. Changing extreme sea levels at European coasts. Coast. Eng. http://dx.doi.org/10.1016/j.coastaleng.2013.10.017 (in press).

Willems, P., 2013. River modelling (in Dutch: Waterloopmodellering). Acco Leuven & Den Haag, 268 p. ISBN: 978-90-334-9296-9, D/2013/0543/132, NUR 955.

Willems, P., Vaes, G., Popa, D., Timbe, L., Berlamont, J., 2002. Quasi 2D river flood modelling. In: Bousmar, D., Zech, Y. (Eds.), River Flow 2002, vol. 2. Swets and Zeitlinger, Lisse, pp. 1253–1259.

Winterwerp, J.C., 2013. On the response of tidal rivers to deepening and narrowing. Risks for a Regime Shift Towards Hyper-turbid Conditions. (http://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Report_Risks_for_a_regime_shift_towards_hyper-turbid_conditions.pdf).

Zanuttigh, B., Simcic, D., Bagli, S., Bozzeda, F., Pietrantoni, L., Zagonari, F., Hoggart, S., Nicholls, R., 2013. THESEUS decision support system for coastal risk management. Coastal Engineering. http://dx.doi.org/10.1016/j.coastaleng.2013.11.013.

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